V. Chayapathy* et al.
(IJITR) INTERNATIONAL JOURNAL OF INNOVATIVE TECHNOLOGY AND RESEARCH
Volume No.4, Issue No.3, April – May 2016, 2985 – 2991.

A study on Voltage Collapse Mitigation by using Voltage Collapse Indices and QV Curves

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Abstract: **Power system stability may be defined as the property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance. The IEEE/CIGRE Joint Task Force has proposed the following definition-"Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded, so that practically the entire system remains intact". Voltage Stability in general, is a condition of equilibrium between opposing forces. In case of power systems, electric power generation and consumption are the opposing forces. Power system stability is the ability of the system to remain in operating equilibrium which is achieved between the electric power generation and consumption. Instability results when a system change or the disturbance leads to an imbalance between the forces in opposition. This paper presents a study on Voltage Collapse Mitigation by using Voltage Collapse Indices and QV Curves.**

Keywords: **Voltage collapse, Mitigation, QV curves, Power system stability**

I. INTODUCTION

Power system stability can be classified as follows: 1. Based on electrical parameters: Rotor angle stability, frequency stability and voltage stability.2. Based on the size of the disturbance: Small scale disturbance (e.g. change in load) or a large disturbance (e.g. failure of a generator).3. Based on the time span to be considered for assessing stability: Short term stability (of the order of several seconds) and long term stability (of the order of several minutes).

Static Voltage Stability Analysis Using Voltage Stability Indices and QV Curves

In the past, conventional power-flow programs using methods like Newton Raphson and Fast Decoupled Load Flow have been used for Static analysis of voltage stability. In Static voltage stability, slowly developing changes in the power system occur that eventually lead to a shortage of reactive power and declining voltage. This phenomenon can be observed by a plot of reactive power transferred versus receiving end voltage. This plot called QV curve was obtained at selected load buses earlier through power flows [33].

Voltage Stability Indices

Voltage stability indices have been formulated which serve as indicators of static voltage stability. These indices enable identification of weak parts of the system and also denote the closeness to voltage collapse. The purpose of voltage stability indices is to locate the weakest bus in the system and the most critical line connected to it. These indices may be based on the lines (line voltage stability indices) or the bus (nodal voltage stability indices)

- Line Voltage Stability Indices are briefly discussed :

1. Line stability index (L_{mn}) :

$L_{mn} = 4XQ_i / ([\sin(\theta-\delta)]^2 \; {*}V_i^2)$ (2.1)

where Q_i: Reactive powers at sending end bus

X=Z sin θ, Z is the impedance of the transmission line

θ : Power factor angle , δ : Voltage angle

V_i : Sending end voltage

The system is stable if Lmn remains less than 1. [2]

2. Line Stability Factor (L_{qp}): This index depends upon real power P_i and reactive power Q_i at the sending end bus.

$Lqp = 4(X/ V_i^2)((X/ V_i^2)P_i^{\,2} + Q_i)$ (2.2)

The system is stable if Lqp remains less than 1. [19]

3. Fast Voltage Stability Index (FVSI): This index depends on the reactive power at the receiving end bus. This index is proposed by L Musirin Et.al. and is defined as

$FVSI = 4Z^2 Q_j / V_i^2 X$ (2.3)

The system is stable if FVSI remains less than 1. [20]

4. Voltage collapse Proximity Index (VCPI):

This index depends on the ratio of real power to maximum value of real power at the sending end and ratio of reactive power to maximum value of reactive power at the sending end. This index is proposed by M. Moghavemmi Et.al. and is defined as

VCPI (P) = Pj / P (max) (2.4)

VCPI (Q) = Qj / Q (max)

Pj and Qj are obtained from load flow analysis and P (max) and Q (max) are the maximum values of active and reactive powers which can be transferred through the line under consideration.

The system is stable if VCPI remains less than 1 [21].

5. On Line Voltage Stability Index (LVSI)

An online voltage stability index is proposed from the view point of the relationships between line active power and bus voltage with the line . If the resistances of the transmission line are zero, then this index fails. The system is stable if LVSI is less than or equal to 1.

LVSI = 4 P_j R / [$V_i \cos(\theta-\delta)]^2$ [22] (2.5)

- Nodal Stability Indices

1. L index: is a global indicator which provides quantitative estimate of distance of actual operating point of system to stability limit

The index L_j can also be derived and expressed in terms of the power terms as the following.

$$L_j = \left| \frac{\overset{*}{S}_{j+}}{Y_{jj+} V_j^2} \right|$$

where,

$$S_{j+} = S_j + S_{jcorr} \qquad (2.6)$$

* indicates the complex conjugate of the vector

$$S_{jcorr} = \Big(\sum_{\substack{i \in Loads \\ i \neq j}} \frac{\overset{*}{Z}_{ji}}{\overset{*}{Z}_{jj}} \frac{S_i}{V_i} \Big) V_j \qquad (2.7)$$

$$Y_{jj+} = \frac{1}{Z_{jj}} \qquad (2.8)$$

The complex power term component S_{jcorr} represents the contributions of the other loads in the system to the index evaluated at the node j [23].

2. Diagonal element dependent index: An index based on partial derivatives of active and reactive powers with respect to voltage angle and voltage which indicates voltage stability.

This work focuses on use of line voltage stability indices in determining critical lines and hence the weakest bus in the power system [24].

Sample Results for IEEE 14 Bus and WSCC 9 BUS System using line Indices

The following section provides the results of studies on an IEEE 14 BUS system. The line indices Lmn and Lpq were used for analysis. Initially no voltage compensating device was included in the system and vulnerable lines were identified. Later voltage compensating devices were connected at bus 14 which has line number 8 and 9 connected to it. The line indices were recalculated and the results are presented below.

Table : Calculation of the line indices for IEEE 14 BUS system

Before compensation			After compensation			
Line No	Lmn	Lpq	SVC		STATCOM	
			Lmn	Lpq	Lmn	Lpq
1	0.015839	0.052840	0.015839840	0.052840	0.015839	0.052840
2	0.017068	0.009396	0.017068	0.009396	0.017068	0.009396
3	0.053552	0.022227	0.053552	0.022227	0.053552	0.022227
4	0.027370	0.010066	0.027370	0.010066	0.027370	0.010066
5	0.041612	0.034816	0.041612	0.034816	0.041612	0.034816
6	0.024181	0.0208960	.024181	0.020896	0.024181	0.020896
7	0.010605	0.009293	0.010605	0.009293	0.010605	0.009293
8	0.7161	0.6512	0.450495	0.215907	0.450495	0.215907
9	2.1938	1.5573	0.575034	0.271811	0.575034	0.271811
10	0.015762	0.028953	0.015762	0.028953	0.015762	0.028953
11	0.144902	0.065728	0.144902	0.065728	0.144902	0.065728
12	0.037997	0.065156	0.037997	0.065156	0.037997	0.065156
13	0.083310	0.075211	0.083310	0.075211	0.083310	0.075211
14	0.102116	0.101549	0.102116	0.101549	0.102116	0.101549
15	0.031704	0.024336	0.031704	0.024336	0.031704	0.024336
16	0.033627	0.039775	0.033627	0.039775	0.033627	0.039775

17	0.370154	0.214176	0.370154	0.214176	0.370154	0.214176
18	0.253349	0.120444	0.253349	0.120444	0.253349	0.120444
19	0.240999	0.182246	0.240999	0.182246	0.240999	0.182246
20	0.145139	0.145139	0.145139	0.145139	0.145139	0.145139

WSCC 9 Bus Test System

This is a Western Systems Coordinating Council (WSCC) test system with three synchronous machines and nine buses. The synchronous machines are provided with exciters. The synchronous machines may be provided with automatic voltage regulators. The system consists of three loads at buses 5, 6 and 8.

Analysis of 9 Bus System using Indices

The 9 bus test system was analysed on similar lines as the IEEE 14 bus test system. The system without any reactive power compensation by FACTS devices was considered and the load buses (5, 6 and 8) were subjected to various loadings. The loadings were of the form of increasing real power alone, increasing reactive power alone and then increasing both real and reactive powers simultaneously. The Newton Raphson power flow program was run for the various loadings and then the load flow results were entered into a MATLAB program which gave the Line Stability Index and Line Stability Factor as outputs. The critical lines were found to be lines 5 and 6 as indicated by the values of indices. These critical lines were found to be either directly connected to or in the proximity of Bus 5. Bus 5 was identified as the weakest bus. FACTS devices (STATCOM/SVC) were connected at Bus 5 and the values of indices were recalculated.

Table : Calculation of the line indices for WSCC 9 Bus Test System.

Before compensation			After compensation			
Line No	Lmn	Lpq	SVC		STATCOM	
			Lmn	Lpq	Lmn	Lpq
1	0.289943	0.300716	0.289943	0.300716	0.289943	0.300716
2	0.217217	0.261616	0.217217	0.261616	0.217217	0.261616
3	0.615306	0.591406	0.615306	0.591406	0.615306	0.591406
4	0.494255	0.479095	0.494255	0.479095	0.494255	0.479095
5	1.2008	1.1592	0.417114	0.227100	0.417114	0.227100
6	0.9004	0.8634	0.575034	0.271811	0.575034	0.271811
7	0.332926	0.366701	0.332926	0.366701	0.332926	0.366701
8	0.311881	0.320035	0.311881	0.320035	0.311881	0.320035
9	0.477638	0.617974	0.477638	0.617974	0.477638	0.617974

Thus it can be observed that insertion of a FACTS device definitely improves the values of line indices and hence mitigates voltage collapse. However it is observed that there is no marked difference in the improvement of the values of the indices with either STATCOM or SVC.

Analysis with QV Curves

The close relationship between reactive power and voltage allows another graphical representation of static voltage stability in the form of a plot between voltages at a bus versus the corresponding reactive power loading of the same bus. As explained in the previous section Bus 5 was identified as the weakest bus. At Bus 5 reactive power (Q) was found at various load voltages (V) first without a FACTS Device and later with a FACTS Device (STATCOM / SVC) and the results are as shown below.

Table : Values of Q and V

V(p.u)	Q WITH NO FACTS DEVICES (p.u)	Q WITH SVC (p.u)	Q WITH STATCOM (p.u)
0.9023	-0.5	-0.5	-0.5
0.8034	-1	-1.0	-1.0
0.7024	-1.5	-1.5	-1.5
0.6076	-2	-2	-2
0.5065	-2.5	-2.5	-2.5
0.4856	-3	-3.37	-3.37
0.4237	-3.17	-3.37	-3.37

II. CONCLUSIONS

Thus it can be observed that insertion of a FACTS device definitely improves the amount of reactive power injected to mitigate voltage collapse. However it is observed that there is no marked difference in the quantity of reactive power injected by the insertion of either STATCOM or SVC. So usage of line indices will not help in in-depth analysis of reactive power management. The concepts of mitigation of voltage collapse is studied by using voltage collapse Indices and values of Q and V. Moderately sized systems such as IEEE 14 Bus and WSCC 9 Bus System are considered.

III. ACKNOWLEDGEMENT

The author thanks Dr.S.Sridhar, Professor and Dean, Cognitive & Central Computing , R.V.College of Engineering, Bangalore, India for guiding him to present his ideas in the form of a paper and communicating it to this journal for publication.

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